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THE ROLE OF SEA ICE AS A PHYSICAL HAZARD AND A POLLUTANT TRANSPORT MECHANISM IN THE BERING SEA

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July, 1980

Prepared for NOAA-OCS

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A Special Report to Outer Continental Shelf
Environmental Assessment Program
From Arctic Research Unit 267

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ABSTRACT

Results of Bering Sea nearshore ice dynamics studies are interpreted in terms of physical hazards to structures and operations related to offshore petroleum exploration and recovery and in terms of ice-related mechanisms for transport of petroleum pollutants, Nine area types are identified and their locations mapped. The area types exhibit sufficiently uniform ice conditions so that ice-related hazards and transport mechanisms are reasonably constant throughout each area. The dominant ice hazards and transport mechanisms are discussed for each area type in terms of the presently most likely petroleum exploration and development methods to be used in these areas.

I. INTRODUCTION

An analysis of ice hazards and pollution transport by ice must necessarily make some assumptions regarding activities taking place which would be subject to hazards or release pollutants. At this time the possibility of petroleum-related activities and pollution problems in the Bering Sea is quite large. For that reason this paper is aimed at exploring the implications of the present state of knowledge of Bering Sea ice conditions in terms of an assessment of hazards and pollution transport related to offshore petroleum exploration and development.

II. BERING SEA NEARSHORE ICE CHARACTERISTICS

The conclusions presented here are based on an analysis of Bering Sea nearshore ice conditions by Stringer (1980). These results are summarized in Figure 1 and are based on analysis of fast ice edge locations and other nearshore ice phenomena observed by means of Landsat imagery and on site-specific observations by Martin (1980), McNutt (1980) and Pease (1980).

In general, it has been found that nearshore ice conditions along the Alaskan Bering coast exhibit a wide range of characteristics from Cape Prince of Wales to the Alaska Peninsula. From Wales to Sledge Island, conditions are largely the same as found along the northern Chukchi coast, while off Nome, fast ice conditions are often similar to Beaufort fast ice. However, as one travels southward along the coast, fast ice is found only in shallower and more shielded locations. Finally, along the perimeter of Bristol Bay, fast ice is located only on mud flats and the upper reaches of estuaries.

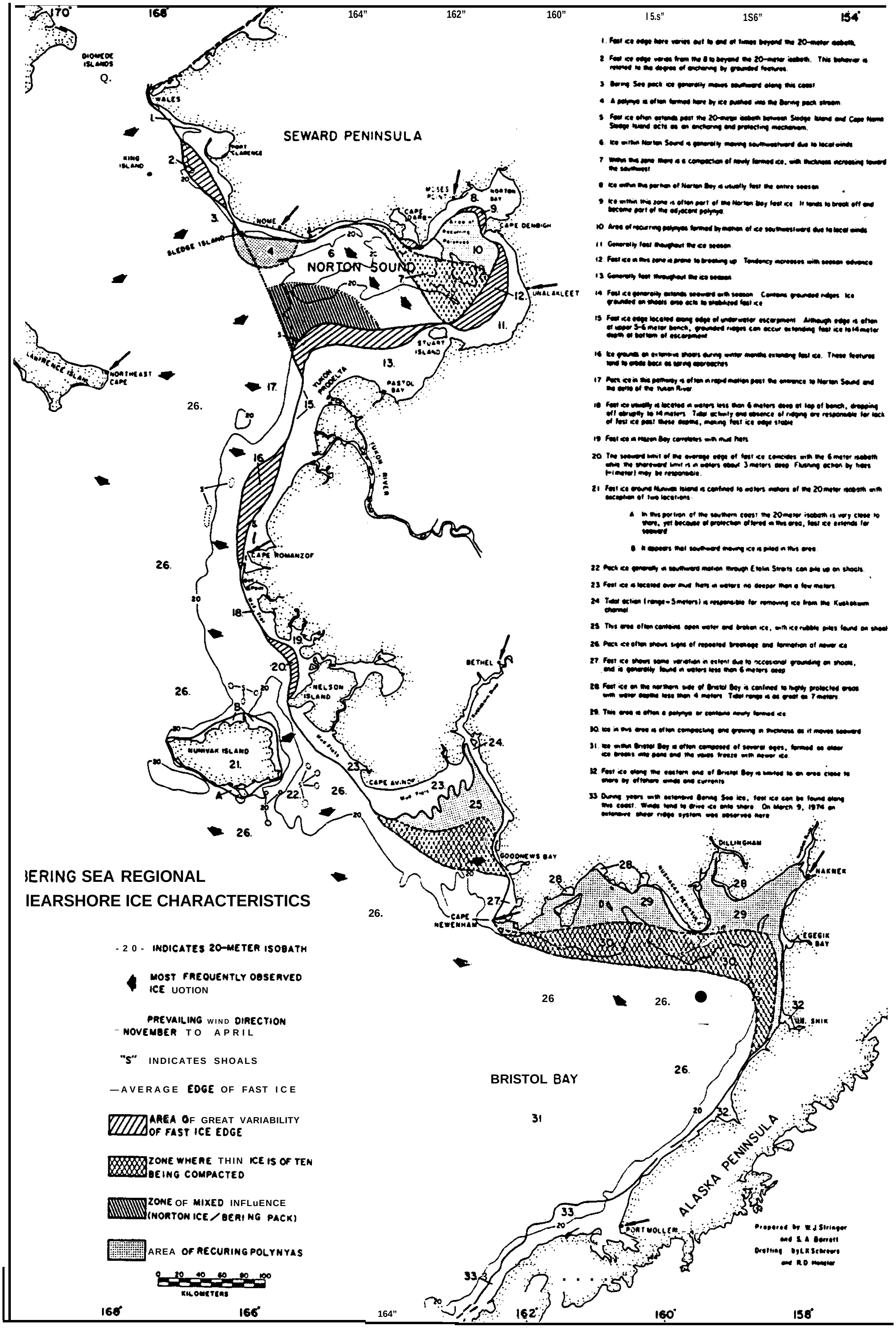

Figure 1. Map of Bering Sea regional nearshore ice characteristics.

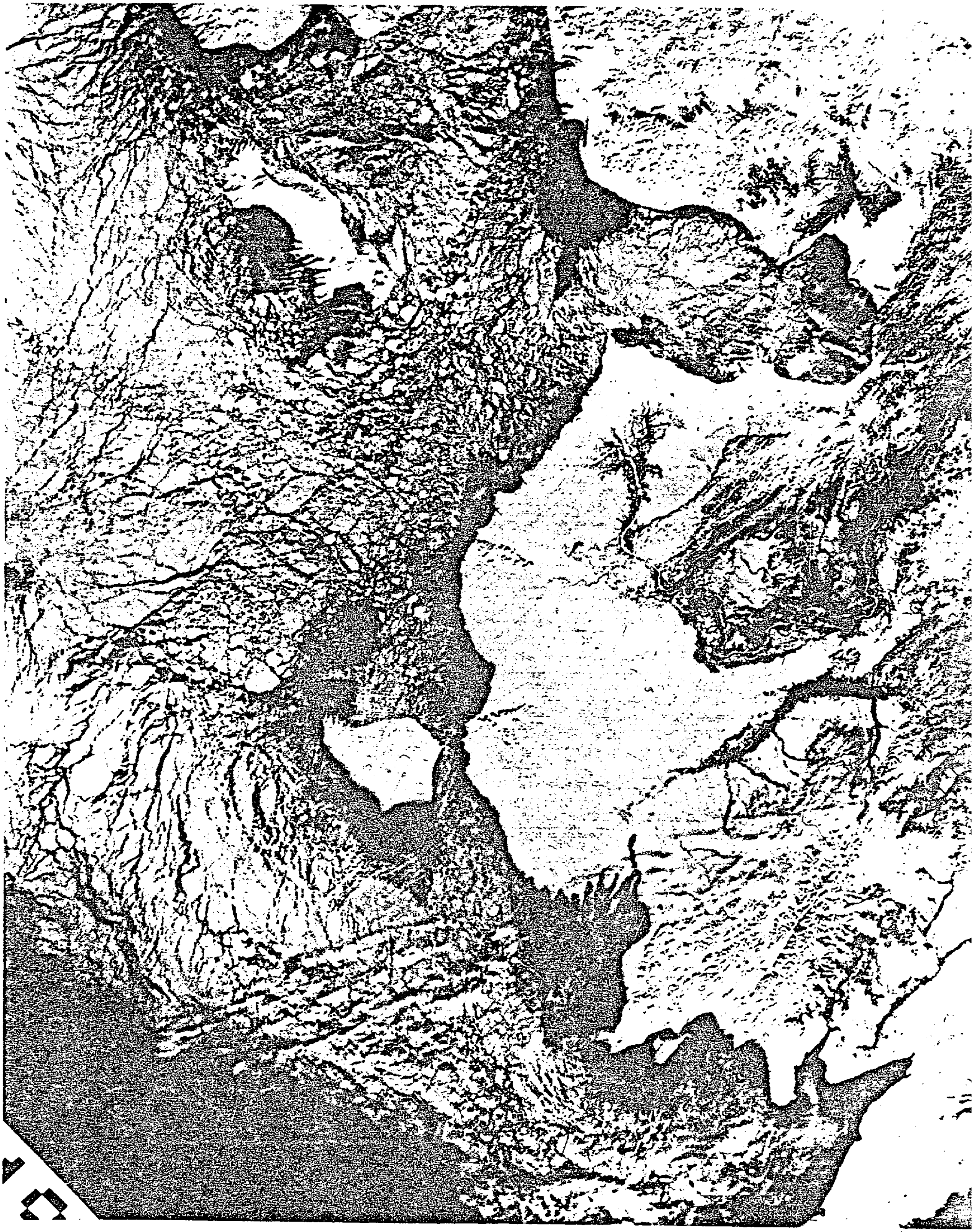

Figure 2. NOAA satellite image of Bering Sea region showing "typical" ice conditions.

Figure 2 is a NOAA satellite image of the entire Bering coast obtained on 19 March 1975. This image illustrates the relationships between pack ice and fast ice conditions described in Figure 1.

III. HAZARDS AND POLLUTION TRANSPORT PHENOMENA ASSOCIATED WITH ICE

Hazards

An assessment of hazards depends on the activities and technologies used in petroleum exploration and development. It is assumed here that in the Bering Sea exploratory drilling will be performed from anchored barges or drillships whenever possible and only in rare instances from man-made islands and platforms. Drillships would be moved into place soon after the break-up of ice and remain on location perhaps into the next ice season. During this time it would be necessary to protect the ship from being moved by ice. Platforms and man-made islands would have to be able to withstand year-round ice conditions and would essentially be used for production structures. Presumably, the type of structure used and its specific design would be based in part on cost versus hazard analyses.

Ice hazards to structures obviously include destruction of the structure or its displacement by ice forces and destruction of facilities on a structure resulting by ice overriding the structure. (For a description of ice override, see Kovacs and Sodhi, 1979). It is not intended here to review detailed considerations given to engineering aspects of these problems. They have been given considerable attention in material published by the National Oceanic and Atmospheric Administration's Outer Continental Shelf Environmental Assessment Program

(NOAA/OCSEAP 1977, 1978, 1979), meetings such as the Bi-annual Port and Ocean Engineering Under Arctic Conditions Symposium (POAC, 1976, 1977, 1979A), special seminars such as the Special Symposium on Gravel Island Construction given by the Exxon Corporation during 1979 (Exxon, 1979), and special reports dealing explicitly with hazards and transport phenomena (OCSEAP 1978B, 1979B). Rather, an attempt will be made to assess the constraints imposed on technology resulting from ice hazards by deline-sting areas where particular hazards will be important to the technology most likely to be used.

Another hazard related to ice arises from its use for transportation and as a platform from which to conduct geophysical surveys or oil spill clean-up operations. This too will be considered in terms of geographical distribution of hazards.

Transport

The problems related to transport of pollutants by ice have been given considerable attention by the Outer Continental Shelf Environmental Assessment Program (NOAA/OCSEAP, 1977, 1978, 1979) and by special groups organized to consider problems specifically related to Arctic oil spills (AMOP, 1979, 1980). The organization of the work has been to study oil spill processes on a non-site specific basis and to construct site-specific oil spill scenarios. For instance, Coon and Prichard (1980) have prepared Beaufort Sea oil spill scenarios for OCSEAP. However, no such scenarios have been constructed for the Bering Sea. Scenario exercises are very constructive studies and can become quite complex because of the number of parameters which can be varied (time and location of spill, specific ice conditions, amount and rate of spill,

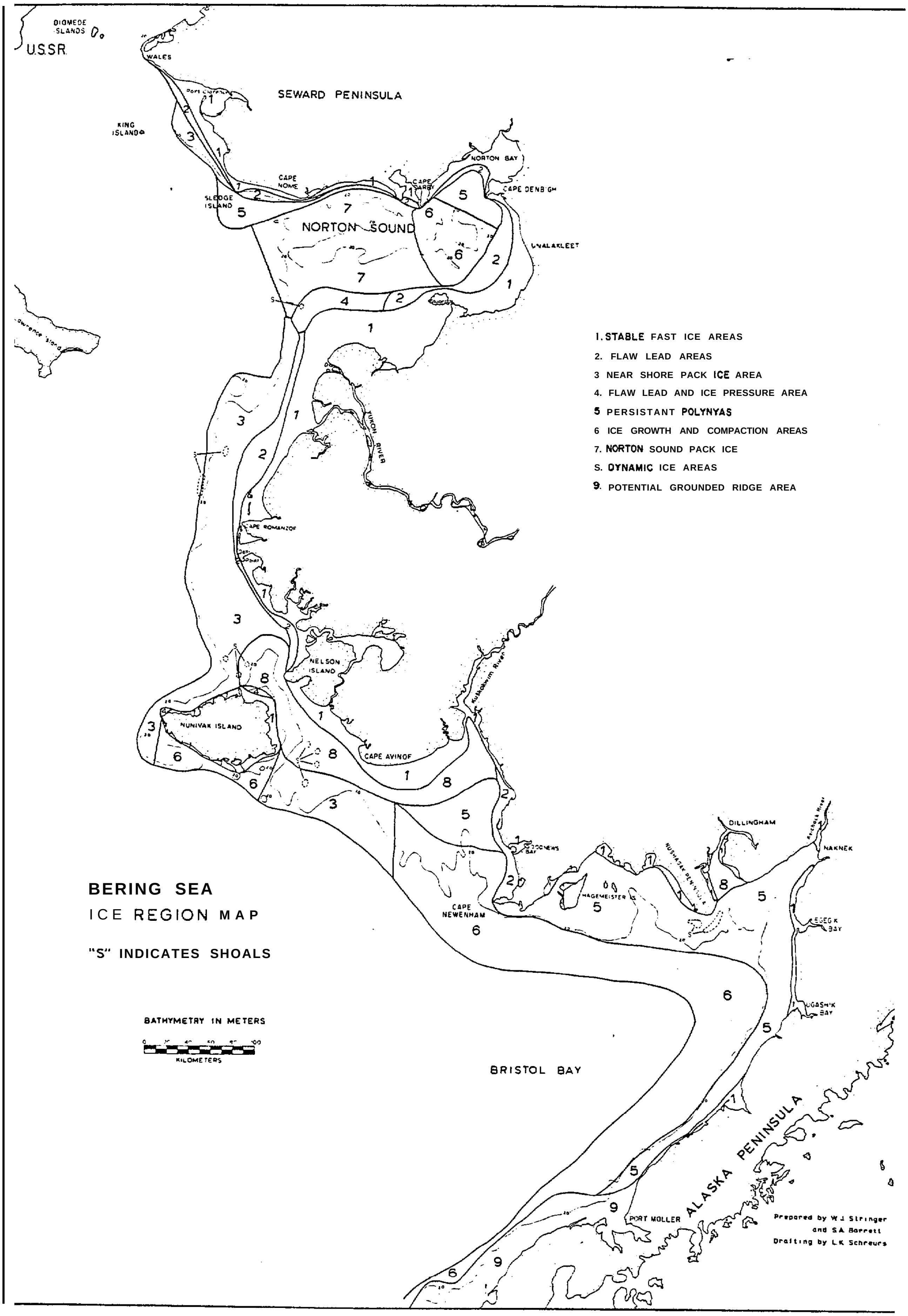

Figure 3. Map of Bering Sea nearshore ice regions.

etc.). Obviously this kind of construction cannot be made easily for the entire Bering Sea Coast and it is not proposed to do so here. Instead, dominant conditions having influences on oil spills will be pointed out. The assessment of transport phenomena presented here is based in large part on a review of these phenomena compiled by Stringer and Weller, (1980).

Figure 3 shows the Eastern Bering Sea nearshore area divided into nine characteristic zones. These zones were defined based largely on regional statistical analyses (Stringer, 1978, 1980) and on site-specific observations (Martin, 1980, Pease, 1980, McNutt, 1980). The following sections contain assessments of ice hazards and dominant pollutant transport phenomena in each of these ten zones.

IV. HAZARDS AND TRANSPORT IN BERING SEA ICE REGIONS

1. STABLE FAST ICE AREAS

These areas contain statistically stable fast ice from winter through late spring. However, Bering Sea fast ice is not nearly as stable as Beaufort Sea fast ice and conclusions should not be drawn based on Beaufort Sea experience. In the Beaufort Sea there is very little tidal variation, and the pack ice is generally held in against the fast ice. In the Bering Sea tidal variations become quite large and the pack ice is advected away from most coasts. As a result, cracks, dislocations, and pile-ups near the ice edge may be encountered at any time of the ice year.

Hazards

During the fall freeze-up, ice pile-ups and overrides could occur within these areas. Since these areas extend from the beach to water depths no greater than 15 m, these areas are likely candidates for artificial gravel islands. Ice override is therefore a major consideration. This hazard is greatest between November and January while fast ice is being formed and during April and May when it is melting and again subject to long range forces.

These areas will certainly be considered for winter surface travel and in particular for winter-time geophysical exploration. Although these areas are the safest for such uses in the Bering Sea region, cautions beyond those exercised in the Beaufort Sea fast ice areas should be taken.

Transport

Oil spill transport associated with ice would most likely occur here between November and late April. During freeze-up between November and late December an oil spill would be associated with at least a partially open ice canopy. The likelihood of incorporation of oil throughout newly-forming ice and subsequent transport with ice is large. This oiled ice could be transported farther toward shore within the "1" area or be advected farther offshore into other areas--perhaps to become Bering Sea pack ice.

Oil spilled between January and April would most likely encounter a closed ice canopy during this time and would tend to remain on the site of its origin. Its spread under the ice would depend largely on under-ice currents. Very little is presently known about under-ice currents in this region but the "1" areas contain the shallowest waters in the coastal region and therefore very likely the strongest tidal currents. A threshold velocity region in the vicinity of 20 cm/sec. exists for a number of under-ice transport mechanisms responsible for moving an oil slick regardless of under ice topography (Cox and Schultz, 1980). Because of the large tidal variations in the portion of this region south of the Yukon River, it is likely that "flushing': of oil will take place in these "l" areas. On the other hand, this process may not take place in the "l" areas well inside Norton Sound.

2. FLAW LEAD AREAS

These areas represent regions where the fast ice edge can vary significantly. Either fast ice or the shore is located on one side and pack ice conditions on the other. Within these regions one could encounter fast ice or pack ice--depending on the location of the fast ice edge. In many respects these are areas of great instability.

Hazards

Because many of these areas are shallow (0-20 m), gravel islands are candidate for exploratory drilling platforms and for production activities. Ice pile-ups and overrides would potentially be constant sources of hazard to operations based on these structures throughout the ice season. If wells were drilled from drillships, production completions would have to be located sufficiently far below the sea floor that ice gouging would not disrupt their operation. Significantly, these "2" areas are major candidates for ice ridging and subsequent plowing of the sea floor by ridge remnants during break-up of the ice. Use of these areas for surface operations would be hazardous but, perhaps possible under carefully monitored conditions.

Transport

Oil spill transport associated with ice in these areas could occur any time within the ice year (November-April). During freeze-up there is a high probability of oil encountering an open ice canopy and becoming pumped upon existing pans and associated within newly-forming ice. There is a very large possibility of subsequent transport of this oiled ice farther offshore, and a lesser (but distinct) possibility of transport toward shore from these areas. An oil spill during winter-spring has a possibility of encountering either a fractured ice canopy or a closed canopy. In the case of a fractured canopy, oil would collect in leads and polynyas and tend to spread laterally. Clean-up operations could be hampered because of difficult and hazardous ice conditions. (Presumably the oil could be burned where it had collected in leads and polynyas).

If a closed ice canopy were encountered, conditions would be similar to those described for the "1" areas, However, the possibility of lateral under-ice spreading due to tidal currents may be diminished in the "2" areas located in deeper waters. On the other hand, some "2" areas lie where oceanic currents may be above the 20-25 cm/sec. threshold required to cause under ice oil slick spreading. In the case of a closed ice canopy being encountered, the possibility always exists for the ice in these areas to be broken up resulting in a mixture of open and closed ice canopy oil spill considerations. Obviously, clean-up operations during closed canopy conditions in these areas would have to be conducted with an eye to the ice becoming broken and transported at any time.

As a result of unstable ice conditions in these areas, there is a significant chance that an oil spill occurring in these areas would become associated with Bering Sea pack ice before the end of the winter ice season.

3. NEARSHORE PACK ICE AREA

Generally these areas contain dynamic ice conditions including the flaw lead defining the seaward extent of fast ice. However, these areas can at times contain pack ice which is temporarily attached to the adjacent fast ice. In addition, several shoals are found in these areas that can be the sites of extensive grounded ridge zones.

Hazards

These areas contain waters between 10 and 25 meters deep and generally contain pack ice during the ice season. Although petroleum exploration and development could be conducted from artificial gravel islands, the cost of these structures compared with other possible drilling platforms--particularly for exploration purposes--would appear to make drillships and free-standing platforms more attractive here than at locations farther toward shore. The pack ice is often driven past the coast in these areas at considerable speeds and the potential for , override of low-lying islands should be examined carefully.

Ridges can be constructed in these areas as a result of interaction of mobile pack ice with grounded ridges defining the edge of fast ice. Free-floating ridges could act as major stress concentrators between pack ice and structures. Production completions located under the sea bed would have to be at such a depth that gouging by these ice features would not be possible. To date there have been no studies to determine whether ocean-floor gouging actually occurs in this region.

These areas may be considered for ice surface operations because of the temporary stability of the pack ice from time to time, but this would be quite dangerous unless means of rapid evacuation were readily at hand as the pack ice can become mobile very quickly.

Transport

An oil spill occurring in these waters would most likely encounter a broken ice canopy. Or if a closed canopy existed at the time of spill it would soon (within a few days) become broken. Bering Sea pack ice in these areas is almost constantly being advected seaward and new ice forming in the leads and polynyas formed as a consequence of this motion. Oil introduced here would be pumped to the surface of existing pans, transported through lead systems and incorporated into newly-forming ice. Transport with Bering Sea pack ice would generally begin immediately. These displacements would most likely be to the south and southwest.

Complex spreading of oil with respect to the ice might result from current shear on the underside of the ice. Bering Sea currents in many areas are northward while winds often drive the ice southwestward. A broken ice canopy would serve to check this spreading somewhat as oil would tend to collect in pools on the "downstream" "side of pans. Weathered oil, however, becoming dense and entering the deep water column would certainly follow the oceanic currents.

4. FLAW LEAD AND ICE PRESSURE AREA

These are areas of dynamic interaction between pack ice and fast ice. Pack ice is driven against grounded fast ice at the entrance to Norton Sound and on the north side of Nunivak Island. As a result, grounded ridges and rubble piles are created in these areas. Occasionally the ice canopy is closed but these areas often contain the flaw leads marking the edge of fast ice.

Hazards

Because of shallow waters in these areas (5-10 m), it appears probable that man-made islands will be seriously considered for exploratory and production drilling sites. The estimated risk of ice override and pile-up based on observations of continuous floe movement is quite large here for the entire ice season and should be investigated further. Furthermore, it is possible that ice stress loading rates may be quite large as well, making continuous and extensive defensive measures necessary. These are dangerous places to conduct surface operations using the ice as a transportation platform as ridging processes are frequent and flaw leads often occur in these areas.

Transport

An oil spill occurring here during the ice season could encounter a variety of conditions ranging from a solid canopy of fast ice to mobile pack ice.

If fast ice exists at the time of a spill, it is possible that spilled oil will remain here for the balance of the ice year. However, spreading due to under-ice currents is a possibility which should be examined. The flaw lead is most likely to be found in this area. Once oil has entered this lead; it is likely that it will soon enter the Bering Sea and participate in the movement of Bering Sea pack ice.

If an oil spill occurs in a portion of this area containing pack ice, two general fates can be expected: 1) The ice becomes fast with the result that the oil largely remains with the ice--perhaps in a quite complex fashion, or 2) The ice enters the Bering Sea, in which case the oil travels more-or-less along with it, perhaps filling leads and polynyas with oil thicker than equilibrium slick thickness.

5. PERSISTENT POLYNYAS

These areas very often contain polynyas or newly-forming ice. Winds in these areas are almost constantly offshore causing movement of pack ice seaward resulting in the formation of open water adjacent to the coastal fast ice.

Hazards

Because of the generally light ice conditions, there may be a temptation to perform drilling in these areas from platforms similar to those currently found in Cook Inlet in the vicinity of Anchorage, Alaska. However, there is absolutely no guarantee that the adjacent pack ice will not be driven shoreward into these areas. If gravel islands were utilized for drilling and operational petroleum extraction, override and pile-up would only be a problem a few times during the year. However, the events would be sudden and defensive measures would be difficult to undertake.

One hazard does exist which may be largely unique to these particular areas: because of the nearly constantly open water combined with very cold surface temperatures, icing of superstructures may be significant.

Obviously the ice surface cannot be utilized in these areas for transportation routes. Before the use of boats is considered for year-round transportation, both ice and icing problems should be studied,

Transport

Oil spilled in these areas will most likely encounter open water or newly-forming ice. In the case of open water, the oil will be transported to adjacent areas (area type 6) where relatively thin ice will be encountered. The interaction of oil with an extensive thin sheet of new ice with very little freeboard has not yet been considered in oil spill studies, and the complete picture of interaction can only be guessed at. It would appear that the slick might, under the proper conditions, mount the surface of a thin, wet sheet of ice and travel some distance across its surface. At the same time, it would also seem possible that oil could also be forced under the ice as well. As the ice thickens, the oil under the ice would tend to be frozen into the ice by encapsulation.

If an oil spill occurred when one of these areas was more-or-less covered with frazil ice, the oil would interact with the ice in a complex way (Martin, 1980). As ice forms in these areas, it is advected to the leeward where it thickens as a result of piling and rafting. An oil slick coating the underside of such ice will doubtless become associated with the ice in a quite complex way following such activity. This ice generally continues to be advected seaward and thicken.

In both cases described here, the fate of the oil would generally be to become associated with newly-formed ice moving to the seaward and be progressively incorporated within that ice as it thickens. Some weathering could occur in the open water case, but with the wintertime temperatures found in these regions, it does not seem likely that much of this could occur before the oil encountered the ice. It is also possible that extensive portions of the ice described here would be oil-coated--especially if the ice was thin when first encountered by the oil. This oil would weather somewhat quickly. Oil spills would be particularly difficult to clean-up in this area because of the extremely hazardous surface conditions.

6. ICE GROWTH AND COMPACTION AREAS

These are areas of newly forming ice adjacent to the areas of nearly constant polynya (area type 5). The ice in these areas is often in motion to the seaward, rafting and piling as it moves. Often several ages of ice are evident--representing a time sequence of ice activity.

Hazards

These areas overlie waters nearly or greater than 20 m deep. The decision concerning which technology to use for a drilling platform would be complex and would involve many factors. It would appear that the possibility of override or pile-up on gravel islands would be a nearly constant threat throughout the ice year. Drillships could be used even into the ice season if proper defensive measures were taken. Large, free-standing platforms could encounter relatively large ice forces--especially if winds reversed from their dominant direction and drove heavy pack ice into these areas. In the deeper areas, under-sea completions become feasible as the possibility of keel gouging by large ice features becomes quite small with these depths.

Considering the nature of the ice in these areas operations utilizing the ice surface are obviously out of the question as are small boat uses. Perhaps larger, ice-strengthened ships could be used in these areas. However, as in the "5" areas, icing could be a significant problem for any structure or ship remaining in the area for any length of time. Because of the ice conditions in this area, oil spills would be very difficult to deal with.

Transport

Oil spilled in these areas would generally encounter growing and compacting ice. The compacting takes place by ridging and rafting which would create pathways for spilled oil to reach the ice surface and become mixed within the ice cover. It would appear reasonable to assume that oil spilled in these areas would become thoroughly associated with the ice--ending up on top of, underneath, and within the ice. Ice in these areas is generally being advected seaward toward the pack ice region. Hence, oiled ice created here would soon become pack ice. Clean-up operations would be extremely hazardous to conduct within this area and perhaps not very effective.

7. NORTON SOUND PACK ICE

This is the interior region of Norton Sound. During the ice season, this area contains pack ice varying in thickness from as thin as 10 to 20 cm in the east and north to more than 70 cm in the southwest. Several ages and thicknesses are often evident. Often older pans are seen held in a matrix of younger ice.

Hazards

Much of this area is deeper than 20 m while the bulk of the remainder is deeper than 15 m. While provision would have to be made for override and pile-up if gravel islands were used for platform purposes, economics may suggest the use of drillships for exploration purposes and under-water completions for production of petroleum. It may be particularly difficult to keep drillships on station here once freeze-up is underway because of the extreme mobility of pack ice in this area. Furthermore, there is some evidence of deep ice keel gouging even in areas of Norton Sound deeper than 20 m (Nelson, et. al. 1980). It would seem therefore, that exploratory drilling in this area might take place from floating platforms during the open water season and production from dredged islands or massive man-made structures (concrete casons for instance).

The ice surface in this area could not be used for long-distance transportation purposes because it is constantly breaking into pans and moving. However, the ice surface could be used for short-term operations such as oil spill clean-up operations provided that extreme meteorological conditions did not exist at the time and that means for rapid evacuation were readily at hand.

Transport

Oil spilled in this area would generally encounter a closed ice canopy during much of the ice year. However, large leads and voids between major pans often characterize the ice morphology in this area. Spilled oil would very likely fill voids beneath the large pans and also flow into any leads and polynyas that exist--perhaps to some depth. Movement of oil beneath the ice would depend on whether the threshold current velocities required to move such a slick had been reached. This ice is constantly undergoing minor ridging of thinner ice between larger pans as leads freeze over and the ice is crushed during compaction events. This process would tend to incorporate oil into ridges. Ice in this area is generally advected into the Bering Sea (see Ray, 1980) where it is transported to the ice front and melts. Hence, oil spilled here could be transported well into the Bering Sea before release and entry into the water column.

8. DYNAMIC ICE AREAS

These are areas of dynamic ice activity where oceanic ice is driven against or past more stable ice resulting in grounded ridges--often on isolated shoals. In these areas the velocities of individual floes can be quite large as a result of nearshore tidal currents and winds.

Hazards

Because of large floe velocities it would be difficult to attempt drilling or other operations from anchored ships during the ice season. Defensive measures would necessarily have to be quite active. Ice does pile up on shallow shoals in these areas at the present. Obviously, similar ice behavior could be expected to occur on man-made islands. Little or nothing is known about the depth of keel gouging in these areas. Ice in these areas should not be considered as a likely platform to conduct surface operations.

Transport

An oil spill would seldom encounter a closed ice canopy. During the ice season the most probable ice condition found would consist of floes surrounded by water and newly-forming ice. Spilled oil would tend to travel seaward (to the south in all these areas) with the ice and currents. Oil would tend to become incorporated into new ice features formed from the recently frozen ice and also be pumped to the surface of low-lying floes, pancakes and other low freeboard ice features. As this oiled ice moves seaward, it would become incorporated into the Bering Sea pack ice. Only then could clean-up operations be considered. Ice in these areas is generally too unstable to be considered as a platform from which to perform clean-up operations.

9. POTENTIAL GROUNDED RIDGE AREA

This area includes the nearshore area between the fast ice along the Alaska Peninsula and the "6" zone located to the seaward. Ice conditions here are generally similar to conditions in the "5" areas except that ice has been observed driven violently along shore creating large shear ridges parallel to the coast.

Hazards

Because of moderation of climate as one proceeds southward, there would be a tendency to regard ice hazards somewhat lightly in this extremely southerly location along the Alaska Peninsula. Although ice conditions here are usually light, large ridges have been observed to form in this area. This would indicate that override and pile-up are real threats to low-lying structures and active defensive precautions would have to be taken against such events. Obviously, these conditions would preclude many other types of structures as well, such as exposed docks and pipeline landings. However, this area generally has rather light ice conditions such as described for a "5" area and, similarly, ice here should not be considered safe for surface transportation.

Transport

As this area is generally open with perhaps some freezing ice being advected offshore, transport pathways are generally those of polynyas described under "5", However, occasionally ice is driven onto shore in this zone. If a spill had occurred just prior to such an event, oil would end up becoming incorporated into piled ice along the coast; in which case, it may eventually terminate its path on the beach or in coastal wetlands.

10. BERING SEA OCEANIC ICE

The discussion to this point has dealt principally with hazards and pollutant transport phenomena related to nearshore ice conditions. While a full treatment of hazards and transport mechanisms related to Bering Sea oceanic ice should be the subject of a complete and independent treatment> perhaps at least a few remarks concerning these subjects should be made here.

At present it appears that over most of the Bering Sea, exploratory wells will be drilled from ships or barges during the ice-free season, thereby avoiding ice-related problems. The possible exception to this might be the necessity for a relief well in the event of a blowout. In that case it might be necessary to extend the possible drilling season for the drilling of relief wells by defensive measures against early season ice around the drill ships.

Production wells may be drilled from ships or ice-resistant structures. In the event that ships are used, the remarks made concerning exploratory wells apply. If bottom–founded, ice-resistant structures are used, ice can be a major factor in the design of these platforms.

Production facilities will necessarily remain in place year-round and will probably involve bottom-mounted well completions and some sort of bottom-founded oil collection and loading structure. The possibility does exist that a combination of under-sea completions and sub-bottom pipelines to shore will be used. However, the absence of ports along the Bering Coast would probably require construction of ice-resistant offshore loading facilities.

Hence it is very likely that the production phase of petroleum development in the Bering Sea will require the construction of ice-resisting, bottom-founded structures in waters generally deeper than twenty meters,

The extent of ice cover varies considerably in the Bering Sea (Niebauer, 1980) and although it is not well documented, it would appear reasonable to expect a wide range of size and strength parameters to be encountered by a structure over the span of its lifetime. In general, one would expect to encounter thicker and stronger ice toward the northern Bering Sea and in particular just south of Bering Strait where large floating ridges may be constructed during “break-out” events of

Chukchi Sea ice into the Bering Sea. There has been some speculation that during these events even multi-year ice has been transported into the Bering Sea. The author is not aware of any documentation showing that this phenomena has taken place.

Hazards

The chief physical hazard related to ice within the Bering Sea area is probably the total force which can be exerted on a "free-standing structure. Secondarily, the design of any such structure must prevent ice from "over riding" the structure. Obviously, a structure could be constructed to withstand the crushing strength of ice throughout its entire cross section at the highest possible loading rate that any reasonable pack ice velocity could create. Any design short of this should be supported by detailed studies of Bering Sea ice morphology, strength and velocities,

Transport

Bering Sea ice is highly mobile and generally follows a north-to-south motion, being completely replaced from three to ten times during an ice season (McNutt, 1980). It seldom, if ever, consists of a solid sheet, but rather consists of a collection of floes of various ages surrounded by leads and polynyas. Often ice is growing in the leads and polynyas and ridges are created as thinner ice becomes trapped between converging floes. Several layers of ice can be found under floes at relatively large angles to the horizontal (Martin, 1980). Because of these factors, one would expect oil spilled in the Bering Sea to become associated with newly forming ice and ridges and be found in leads and polynyas. Very little oil would become trapped beneath large floes. The oiled ice would be expected to move generally southward. However, other motions could take place, particularly over short (3-7 day) periods. During winter, fast ice along the adjacent shores would prohibit oiled ice from entering coastal areas.

The work of Pease (1980), McNutt (1980), Martin (1980), and others strongly suggests that oiled ice in the Bering Sea will move southward to the ice front where it will melt, allowing the oil to enter the water column. The significance of this possibility is that all ecosystems along this vector are endangered by this process. The exception to this southward motion rule might be found in spring, when Bering Sea ice has been observed moving northward into the Chukchi Sea during the general breakup and melting of pack ice.

Clean-up of spilled oil in the Bering Sea would be nearly impossible because of the nature of the association of oil with ice as described above, coupled with the danger to crews attempting to operate on the pack ice. Perhaps some burning of pooled oil could be accomplished by dropping igniting devices from aircraft.

DISCUSSION

The assessment of Bering Sea ice-related hazards and pollutant transport phenomena presented here is obviously a “first cut” treatment of these subjects. However, a more detailed examination would depend on a better understanding--on a site specific basis--of ice conditions and dynamics in the areas to be considered in terms of hazards and transport. Among the parameters to be measured would be: ice thicknesses and velocities, currents, local winds, tidal variations, and ridge height statistics. To date, these kinds of studies have been strikingly absent in the nearshore areas of the Bering Sea and have only begun in the oceanic portion of the Bering Sea.

ACKNOWLEDGEMENTS

This work was supported by the Bureau of Land Management through an inter-agency agreement with the National Oceanic and Atmospheric Administration, under which a multi-year program responding to an environmental assessment of petroleum development on the Alaskan Continental Shelf is being performed. Specifically, Contract 03-5-022-55, research units 265, 258 and 257 supported the work described here. In addition, the author would like to thank Dr. Gunter Weller, Dr. Seelye Martin, Ms. Lyn McNutt and Ms. Carol Pease for helpful discussions. It should be stressed that the material contained in this paper--in particular, assumptions concerning petroleum development scenarios--is highly subjective and the author accepts full responsibility for any errors or omissions in this presentation.

REFERENCES

AMoP, 1979. Proceedings of the Arctic Marine Oil Spill Program Technical Seminar, Fisheries and Environment Canada, Environmental Emergency Branch, Ottawa, Canada.

AMOP, 1980. Proceedings of the Arctic Marine Oil Spill Program Technical Seminar, Research and Development Division, Environmental Emergency Branch, Environmental Protection Service, Ottawa, Ontario, Canada K1A1C8.

Coon, M. and R. Prichard, 1980. The Transport and Behavior of Oil Spilled in and under Sea Ice. Final Report of Outer Continental Shelf Environmental Assessment Project Research Unit #567. To be published by NOAA/OCSEAP Field Office, P. O. Box 1808, Juneau, Alaska 99802.

Cox, J. C. and L. A. Schultz, 1980. The Transport and Behavior of Spilled Oil under Ice. Published in the Proceedings of the Third Arctic Marine Oil Spill Program Technical Seminar. Research and Development Division, Environmental Emergency Branch, Environmental Protection Service, Ottawa, Ontario, Canada K1A1C8.

EXXON, 1979. Proceedings of a Technical Seminar on Alaskan Beaufort Sea Gravel Island Design. EXXON Production Research Company, Anchorage, Alaska.

Kovacs, A. and D. S. Sodhi, 1979. Ice Pile-up and Ride-up on Arctic and Subarctic Beaches. Proceedings of the Fith International "Conference on Port and Ocean Engineering under Arctic Conditions, Norwegian Institute of Technology, University of Trondheim, Trondheim, Norway. Pages 127-146,

Martin, S. 1980. Anticipated Oil-Ice Interactions in the Bering Sea. in The Eastern Bering Sea, its Oceanography and Resources. OCSEAP, Outer Continental Shelf Environmental Assessment Program. NOAA Field Office, P. O. Box 1808, Juneau, Alaska 99802.

McNutt, S. L., 1980. Remote Sensing Analysis of Ice Growth and Distribution in the Eastern Bering Sea. in The Eastern Bering Sea, its Oceanography and Resources. OCSEAP, Outer Continental Shelf Environmental Assessment Program, NOAA Field Office, P. O. Box 1808, Juneau, Alaska 99802 (in press).

Niebauer, H.J., 1980. Recent Fluctuations in Sea Ice Distribution in the Eastern Bering Sea. in The Eastern Bering Sea, its Oceanography and Resources. OCSEAP, Outer Continental Shelf Environmental Assessment Program, NOAA Field Office, P.O. Box 1808, Juneau, Alaska 99802 (in press).

OCSEAP, 1977, 1978A and 1979A. Annual Reports of Principal Inv"estigators, ' OCSEAP Program Office, NOAA ERL RX4, Boulder, Colorado 80302.

OCSEAP, 1978B. Interim Synthesis Report: Beaufort/Chukchi, OCSEAP Program Office, NOAA ERL RX4, Boulder, Colorado 80302.

OCSEAP, 1979B. Environmental Stipulations Relating to OCS Development of the Beaufort Sea, Special Bulletin #25, OCSEAP, NOAA/Arctic Project Office (University of Alaska), Fairbanks, Alaska 99701.

Pease, C. H., 1980. Eastern Bering Sea Ice Dynamics and Thermodynamics. in The Eastern Bering Sea, its Oceanography and Resources. OCSEAP, Outer Continental Shelf Environmental Assessment Program, NOAA Field Office, P. O. Box 1808, Juneau, Alaska 99802 (in press).

POAC, 1976. Proceedings of the Third International Conference on Port and Ocean Engineering under Arctic Conditions, Institute of Marine Science, University of Alaska, Fairbanks, Alaska 99701.

POAC, 1978. Proceedings of the Fourth International Conference on Port and Ocean Engineering under Arctic Conditions, Memorial University of Newfoundland, St. John's, Newfoundland, Canada.

POAC, 1979. Proceedings of the Fifth International Conference on Port and Ocean Engineering under Arctic Conditions, Norwegian Institute of Technology, University of Trondheim, Trondheim, Norway.

Ray. V.M. and W.R. Dupre', 1980. The Ice-Dominated Regimen of the Norton Sound Region of Alaska. in The Eastern Bering Sea, its Oceanography and Resources. OCSEAP, Outer Continental Shelf Environmental Assessment Program. NOAA Field Office, P.O. Box 1808, Juneau, Alaska 99802,

Stringer, W. J. 1978. Morphology of Beaufort, Chukchi and Bering Seas Nearshore Ice Conditions by Means of Satellite and Aerial Remote Sensing. Final Report, NOAA/Arctic Project Office (University of Alaska), Fairbanks, Alaska 99701.

Stringer, W. J., 1980. Fast Ice Characteristics in the Eastern Bering Sea. Preprint. Published as Geophysical Institute Report. Geophysical Institute, University of Alaska, Fairbanks, Alaska 99701.

Stringer, W. and G. Weller, 1980. Studies of the Behavior of oil in ice, conducted by the Outer Continental Shelf Environmental Assessment Program. To be published in the Proceedings of the Arctic Marine Oil Spill Program Technical Program, Edmonton, Alberta, Canada June 3-5, 1980, by Environment Canada, Environmental Emergency Branch, Ottawa, Canada.